Snowmass2021 - Letter of Interest

[Time Delay Cosmography in the 2020s]

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: Gravitational time delays are poised to be a major probe of cosmology in the 2020s. In the 2010s, samples of only a few lensed quasars have been demonstrated to yield precise measurements of the Hubble constant, and the first multiply imaged supernova has been discovered. With the Rubin, Euclid, and Roman observatories, relevant samples will increase in size by orders of magnitude. In order to exploit these systems to determine the expansion history of the universe, constrain the nature of dark energy, and investigate physics beyond ΛCDM, the bottleneck will be follow-up. The top priority for SNOWMASS2021 is the Time Delay Machine (TDM), a 3-4m class telescope with wide field imaging for high precision/cadence monitoring to determine time delays. At lower priority, an integral field optical spectrograph on the same telescope would enable redshift determination for lensed sources and nearby perturbers. In parallel, it is key to continue to support the development of adaptive optics from the ground for high resolution imaging and spectroscopy.

Background.

The measurement of cosmic distances plays a central role in our understanding of cosmology and fundamental physics. By mapping the expansion history of universe and therefore its underlying dynamics and constituents, distance measurements were key to the discovery of dark energy [17;19]. More recently, the tension between the Hubble constant H_0 measured in the late universe and the value extrapolated from early universe probes in a ΛCDM cosmology [27], serves as a reminder of the importance of determining percent level distances with a variety of probes.

Strong-lensing gravitational time delays [18] provide a one step measurement of a ratio of angular diameter distances (known as the time-delay distance), providing a powerful and independent alternative to more traditional methods. Given the typical redshift distribution of strong lens sources and deflectors, time delays probe primarily the expansion history of the universe in the redshift range $z = 0 - 1$ with some constraining power to higher redshift. They are thus ideally suited to probe the epoch of emergence of dark energy and measure H_0. A sample of 40-100 time delay distances can determine H_0 to percent precision [3;12;20], as well as deliver substantial improvements in the figure of merit of dark energy for Stage IV experiments [28].

In practice, accurate and precise time delay cosmography requires the following ingredients [25]: 1) time variable strongly lensed sources; 2) precise measurements of the time delays between multiple images; 3) high fidelity mass models of the main deflectors; 4) characterization of the effect on the time delay from the distribution of matter along the line of sight to the source. In the past decade, a combination of observational, computational, and methodological breakthroughs has enabled progress on all four fronts [5;21;29]: 1) more than 100 lensed quasars and the first lensed supernovae have been discovered [10;26]; 2) high cadence monitoring with millimag photometry measured time delays to percent precision [6]; 3) lens modeling of high-resolution images [5;22] plus stellar kinematics [24]; 4) estimating the line of sight effects from number counts [8] and weak lensing measurements [23] coupled with cosmological numerical simulations.

The way forward: opportunities and challenges

The abundance of lensed quasars and supernovae soon to be discovered by the Rubin, Euclid, and Roman Observatories will be an amazing opportunity for time delay cosmography. The *top100* sample (e.g. 100 quadruply imaged quasars or supernovae with time delays in the range 30-100 days and with deflectors bright enough for detailed kinematics) will be selected for in depth studies. The larger samples will be available to expand the statistical power of the method based on the lessons learned from the detailed studies.

The real bottleneck will be the availability of high quality data of the *top100* sample to complement those obtained from the surveys themselves (including information on the line of sight): 1) high precision time delays; 2) spectroscopy for redshifts and stellar kinematics; 3) high resolution imaging and spectroscopy. Unlike traditional cosmological probes that are well suited to a single self contained experimental design, eliminating the bottleneck will require the development of two parallel tracks: a 3-4m class telescope dedicated to monitoring (and, ideally, spectroscopy for redshifts); the James Webb Space Telescope (JWST) and adaptive optics assisted large (8-10m) and extremely large (24-39m; ELTs; for the US the US-ELT Program) telescopes from the ground for high resolution imaging [14] and spatially resolved kinematics [3;20].

1. The Time Delay Machine: A 3-4m-class telescope dedicated to time delay cosmography.

Multi-decade experience with COSMOGRAIL [15] has shown that stability and control over the schedule is a key factor in the success of any monitoring program. While Rubin might deliver 100s of quasar time delays and discovery hundreds of lensed SN over its 10-year life time [7;11;16], only with a dedicated telescope can one achieve single-season time delays at a few percent precision and build up the *top100* sample rapidly enough to achieve breakthroughs in this decade. Control over the schedule is particularly critical to realise the promise of lensed SNe. Lensed SN time delays can be most easily measured in the first few weeks after explosion[7;9]. Typically fainter and with shorter time delays than lensed quasars these targets require an early investment of telescope time to yield few percent precision time-delays. It is therefore important to have the ability to reallocate observing priority to a lensed SN in the rare times that a promising target is live.

The observational requirements for monitoring are millimag relative precision with daily or quasi-daily cadence, and median image quality of arcsecond or better for deconvolution of blended sources and foreground deflector. In practice, since the bulk of the *top100* sources will have i-band magnitudes in the range $i \sim 20 - 22$, this requires a 3-4m class telescope in a good site, in order to complete the monitoring well within the decade. In terms of instrumentation, the top priority is an optical imager with field of view of $10 - 30'$ to capture reference stars. A non-thermal infrared channel to the imager would provide additional gains for supernovae light curves. Second priority in terms of instruments is a optical integral field spectrograph with field of view of 10-30" that would deliver redshifts for the lensed sources (especially the time critical supernovae) and nearby perturbers. Some spectroscopy will be available from surveys like DESI or 4MOST, but a dedicated spectroscopic capability will accelerate the collection of the detailed spectroscopy needed for the study of the *top100* sample, and be crucial for real time spectroscopy of lensed supernovae.

The Time Delay Machine (TDM) experiment can be realized by re-purposing an existing 3-4m class telescope (or a fraction of one in the North and of one in the South for full hemispheric coverage; or a set of high performance 2m class telescopes). In some cases existing instrumentation is sufficient, in others it will have to be built. A non-exhaustive list of telescopes that would be a strong foundation for TDM includes: 4.1m SOAR; 4m Blanco; 4m VISTA; 3.8m UKIRT: 3.5m NTT; 3.5m Galileo; 3.5m Starfire USAF; 3.5m WIYN Arizona; 2.6m VST; 2.6m NOT; 2.2m MPIA; 2×2m LCOGT. A newly built fully robotic telescope would also be excellent of course,

2. High resolution imaging and spatially resolved kinematics.

Beyond time delays and redshifts, the other pieces of information required for time delay cosmography are high resolution imaging for astrometry[2] and modeling of the extended lensed features, and stellar kinematics, preferably spatially resolved, to constrain the mass profile of the main deflector breaking the mass sheet degeneracy[3;4;31]. These observables require angular resolution of 100mas or better and large collecting area. The imaging part can be carried out with the Hubble Space Telescope, JWST, high strehl adaptive optics on large and extremely large telescopes. Rubin and Euclid will not have sufficient resolution and/or depth, while Roman may be sufficient only for the brighter systems[14]. Spatially resolved kinematics will require JWST or substantial improvements in AO technology and instrumentation on large telescopes [13;30], or AO-fed extremely large telescopes. Due to the finite lifetime of the mission – and the expected pressure for time – JWST will likely be limited to relatively small samples of the brighter targets, while ELTs (US-ELTP for the US) will be essential to complete kinematic follow-up of larger *top100* samples[1]. Continued support of adaptive optics on large and extremely large telescopes is crucial to realize the power of time delay cosmography in the 2020s.

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